Renewable and Sustainable Energy Reviews 25 (2013) 393–403

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Material constraints for indigenous production of CdTe PV: Evidence from a Monte Carlo experiment using India's National Solar Mission Benchmarks

Dwarakanath Ravikumar [a,1], Deepak Malghan [b,*]

[a] School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287, USA
[b] Centre for Public Policy, Indian Institute of Management Bangalore, Bannerghatta Road, Bangalore 560076, India

ARTICLE INFO

Article history:
Received 22 November 2012
Received in revised form
16 April 2013
Accepted 20 April 2013
Available online 31 May 2013

Keywords:
Energy security
Life Cycle Analysis
Tellurium Supply Constraints

ABSTRACT

Thin film solar photovoltaic (PV) technology, especially installations based on cadmium-telluride PV cells (CdTe) are expected to play a major role in future expansion of the global installed base of solar power. India's National Solar Mission (JNNSM) is an ambitious program to bootstrap the Indian solar sector. JNNSM seeks to use solar energy to supply India's growing energy needs, help reduce India's reliance on imported fossil fuels, address social issues such as the need to provide access to basic electricity to India's rural population, and jump-start an indigenous solar manufacturing industry. Using a Monte Carlo approach to simulate combinations of future technology, policy, and market scenarios, we estimate the amount of Cd and Te needed for indigenous manufacture of CdTe solar modules using JNNSM targets as a benchmark for new capacity addition. We show that complete indigenous production of CdTe cells using Te recovered from Indian copper refining process is not feasible even if JNNSM were to succeed in its objective of developing indigenous capacity for advanced PV manufacturing technology.

Contents

* Corresponding author. Tel.: +91 80 2699 3355; fax: +91 80 2658 4050.
E-mail addresses: dtriplic@asu.edu (D. Ravikumar), dmalghan@iimb.ernet.in (D. Malghan).
[1] Tel.: +1 602 715 6657.

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http://dx.doi.org/10.1016/j.rser.2013.04.030

1. Introduction

New renewable energy configurations that rely on relatively less-abundant elements for both generation and battery storage have now become mainstream. Consequently, material resource scarcity and collateral environmental consequences of the life cycle material flows have attracted increasing attention in recent years [4,5,21,66,80,81]. There are concerns about the continued availability of critical rare earth elements, as well as the research investments needed to overcome these material bottlenecks [2,57]. Among renewable sources, electricity produced from solar photovoltaic (PV) technology is seen as an important part of any reasonable energy mix that tries to address greenhouse gas emissions induced climate change, and extend electricity to an estimated 1.3 billion people around the world who currently lack access to electricity [51]. Governments also view PV as a strategic investment from at least three different perspectives: first, through lesser dependence on imported fossil fuel, PV can contribute to national security [50]; second, by helping to reduce GHG emissions, PV contributes to national environmental goals [32]; and finally, by adding industrial capability and jobs in a rapidly growing sector, PV can help provide a boost to national economies [88].

Non-silicon thin film alternatives have been increasing their share of the total installed PV-solar base [14]. In particular, cadmium telluride (CdTe) PV technology has been making rapid strides in recent years. The global market share of CdTe among all competing PV technologies rose from 2% in 2005 to 13% in 2011 [20]. CdTe panels account for less than 1% of the global economy generated throughput for primary cadmium [72]. However, there are concerns about the continued availability of tellurium [5,21,72]. Resource constraints are closely related to system costs, technological progress, and environmental impacts [29]. While the CdTe PV modules in the future (2038 and beyond) can be made out of recycled tellurium from end-of-life modules, such a scenario is crucially contingent on substantive improvement in material efficiency and development of large recycling programs [59]. In a recent paper, Woodhouse et al. identify pathways for technological progress that can address material bottlenecks surrounding CdTe PV [89].

While global material constraints have received much attention, the possibility of material throughput constraints at the national level will become increasingly important as nations begin to look at renewable energy systems as strategic alternatives to fossil energy. In this paper, we investigate the potential material constraints that a country might face if it attempted indigenous production of CdTe PV. We employ India's ambitious solar energy program, the Jawaharlal Nehru National Solar Mission (JNNSM) — named after India's first Prime Minister — as a case study to examine the nexus between material constraints at the national level and the diffusion of renewable energy systems [35,41]. JNNSM is closely linked to India's strategic interests in terms of both energy security and international climate negotiations. It aims to simultaneously address the twin issues of energy security and energy poverty [74]. JNNSM potentially accords India a chance to move from being a 'norm taker to a norm maker' as a significant player in the global energy market, and as a participant in global climate change deliberations [18]. The solar mission is one of the constituents of the National Action Plan on Climate Change (NAPCC) announced by India in 2008 [36]. While both the JNNSM and NAPCC emphasize transfer of clean energy technology, there has been little progress so far on this front [46]. India has little choice but to invest in developing an indigenous solar industry given the nexus between energy poverty, climate change, and energy security [74].

The remainder of the paper is organized as follows. In Section 1.1 we summarize India's National Solar Mission (JNNSM) and show why it represents a useful benchmark for exploring indigenous material constraints for future growth of CdTe PV technology. In Section 2 we summarize the theoretical, engineering, and economic reasons that explain the rapid growth, and future potential of CdTe PV. In Section 3, we present a critical review of material constraints surrounding further development of CdTe PV. We show how tellurium rather than cadmium will be the binding material constraint even after accounting for environmental concerns surrounding the use of cadmium. In Section 4 we model tellurium requirements using JNNSM annual targets as benchmarks under a variety of policy, market, and technical scenarios using a Monte Carlo (MC) model. We conclude in Section 5. In Fig. 1 we summarize our approach on building the Monte Carlo model for tellurium using JNNSM targets.[2] Fig. 1 shows how we combine policy and technology parameters to inform our Monte Carlo assumptions.

1.1. JNNSM

JNNSM aims at a massive scaling up of India's installed base of solar energy (both solar thermal and PV). The national solar mission aims to add a cumulative total of 32 000 MW of grid-connected PV; 3200 MW of off-grid PV; and 42 million square meters of solar thermal collectors between 2010 and 2022 [35]. In the first phase of the Solar Mission, 150 MW and 350 MW of PV capacity were slated to be added in two batches. After the actual bidding process, power purchase agreements (PPAs) were signed for a total of 140 MW in Batch-1, and 340 MW in Batch-2. Phase-2 of the Solar Mission is slated to begin in 2014 [41]. Currently, India has a grid-connected PV installed base of little over 30 MW [62]. Even in the early phases of the program, JNNSM calls for annual PV targets of 375 MW (Table 1). This 13-fold increase in the total grid interactive PV capacity in the very first phase of the program means that modeling policy and market variables cannot fully rely on past experience.

In addition to the strategic importance of JNNSM from a national energy security perspective, it also holds promise to potentially address the acute energy poverty problem in India where around 288 million people do not have access to grid electricity [51]. JNNSM has been critiqued for inadequately addressing this crucial equity question. Although extending electricity access through stand-alone small decentralized systems is an important mission objective, the subsidy structure is skewed towards larger grid interactive systems [13,45]. From a governance and execution perspective the initial roll-out of projects under JNNSM has been mired in controversies, irrational bidding, and an unprepared regulatory structure [8,71,90]. Despite these criticisms, JNNSM is likely to remain central to India's strategic and

[2] We are grateful to an anonymous reviewer for the flowchart.

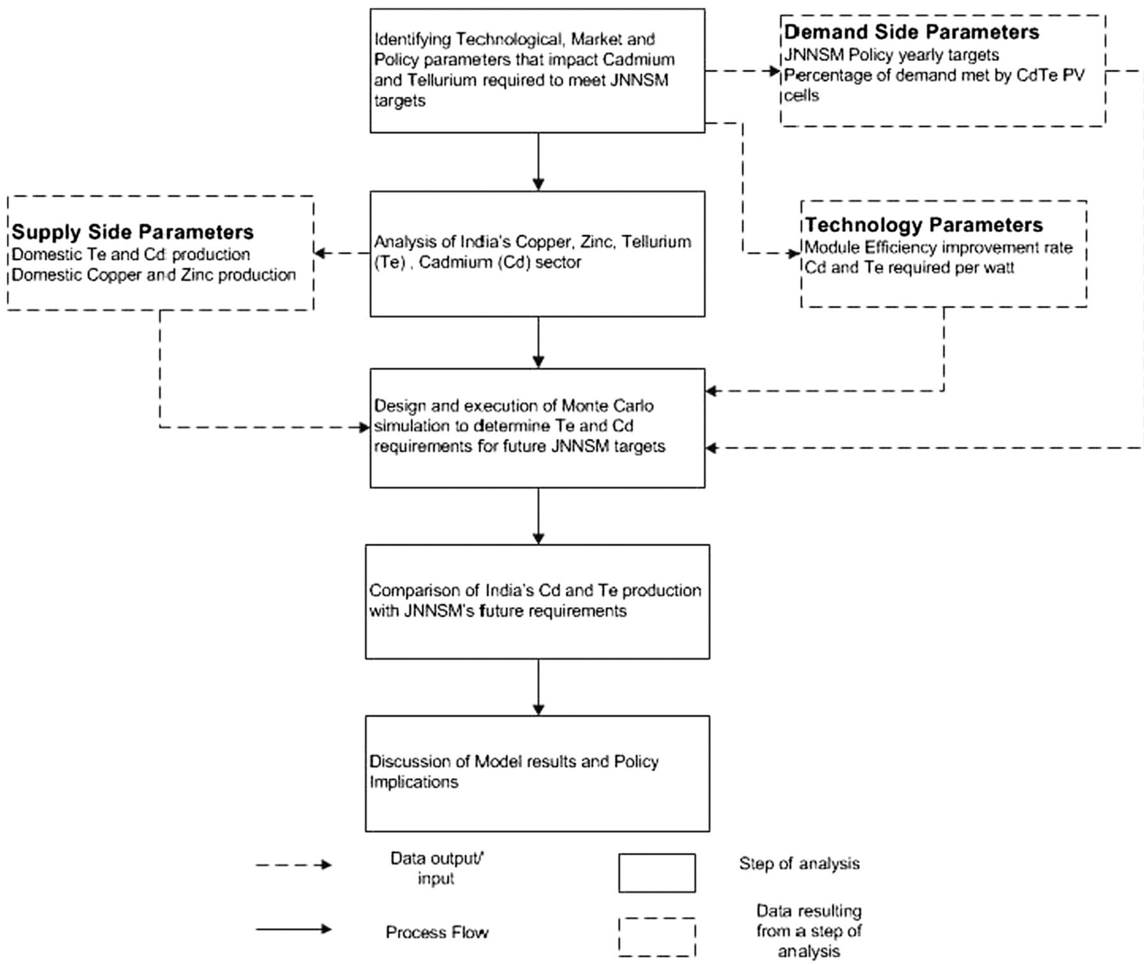


Fig. 1. The chart describes the key steps involved in the development of the Monte Carlo model for tellurium requirements using JNNSM targets.

Table 1
JNNSM targets and Monte Carlo experiment assumptions. Targets are official JNNSM numbers [35]. The annual capacity addition numbers in the last column are computed by assuming that the first two phases realize the median between low and high end targets for grid-interactive PV. We use these annual numbers as one of the inputs to the Monte Carlo model.

	Off-grid PV Target (MW)	Grid-interactive PV Target (MW)	Annual Grid PV Capacity Addition (MW)
Phase I (2010–2013; 4 years)	200	1000–2000	375
Phase II (2013–2017; 4 years)	1000	4000–10 000	1750
Phase III (2017–2022; 5 years)	2000	20 000	4000

social sector goals. Ref. [70] reviewed 'hotspots of solar potential in India' as regions with a confluence of solar potential (based on an average insolation and land availability), techno-economic potential, and organizational potential. With 58% of the Indian landmass receiving an insolation of at least 5 kWh/m^2/day, even under conservative assumptions about land availability, techno-economic and organizational feasibility, the JNNSM targets are technically achievable [70].

Currently, the Indian PV market is dominated by silicon-based technologies with nearly 90% of the total PV modules manufactured in India using crystalline silicon technology [52]. While silicon alternatives within India are in a nascent state of development, India is seen as one of the major destinations for new shipments of such PV panels [78]. India contributed around 8% of First Solar's sales in 2011 after the announcement of JNNSM [22]. Abound Solar, a thin film CdTe manufacturer has signed an agreement with an Indian PV manufacturer to set up a 1 MW project in India [1]. Given the magnitude of JNNSM targets and its strategic importance to India's energy security, it is likely that future JNNSM projects will continue to use a mix of PV technologies including thin films such as CdTe, and emerging cost-effective Si based PV technologies such as upgraded metallurgical grade silicon (UMG-Si). In the power purchase agreements already contracted under JNNSM, thin films account for approximately 50% of the total [41, p. 15]. The next section briefly reviews why CdTe technology will be an important part of this mix.

2. Competing PV technologies

The global installed base of CdTe cells has increased from 1% of total PV in 2005 to 9% in 2009 [67].

Fig. 2 shows the global growth of CdTe cells in the 10-year period between 1997 and 2008. One single manufacturer, First Solar, currently dominates the industry. In 2010, First Solar shipped 1412 MW out of the total of 1430 MW of CdTe PV modules [43,22]. India is a growing market for First Solar's CdTe modules. First Solar has shipped 200 MW in 2011 (Quarter-1) to India and has contracted another 250 MW for 2012 [23]. In this section, we briefly review the technical and economic factors that will

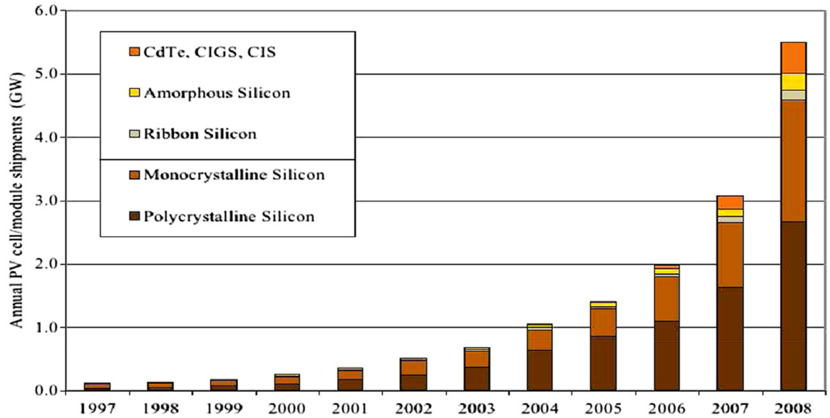


Fig. 2. Global growth of competing PV technologies [14].

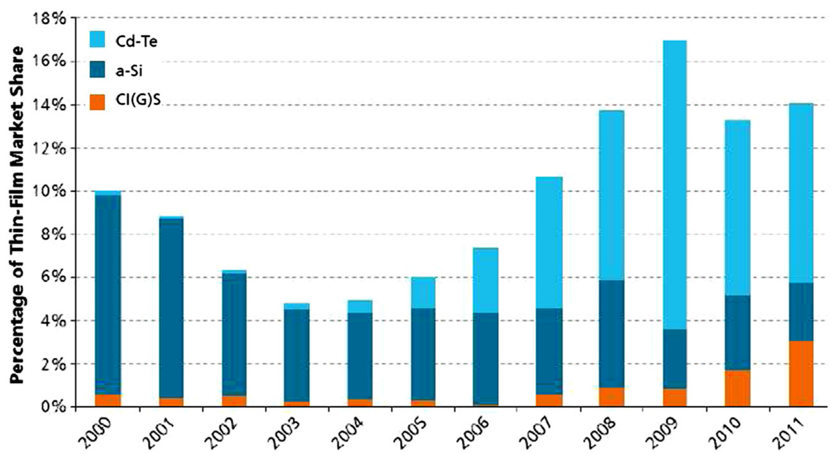


Fig. 3. Relative global market shares of competing thin film technologies as a percentage of worldwide PV production. Chart reproduced from [27].

continue to support the strong growth of installed CdTe capacity around the world, and in India through the JNNSM program.

Among competing PV technologies, CdTe modules have the lowest cost per installed watt. First Solar's CdTe cells breached the one-dollar per watt for the first time in 2008 [22]. A recent techno-economic assessment of various PV technologies showed that CdTe possesses the lowest levelized cost (LCOE) under diverse assumptions about solar insolation, market conditions, and risk of deployment in emerging markets [67]. The full deployed cost including balance of system (BOS) components for a CdTe systems was found to be between 13.3 EUR cents/kWh and 19 EUR cents/kWh depending on exact location of the installation [67]. Estimates of manufacturing costs for thin film and crystalline silicon technologies have placed CdTe at the lowest level [69]. Fig. 3 compares CdTe with other competing thin film PV technologies. Even as there has been a rapid expansion of the global PV industry with costs falling across all technologies, thin film modules account for over 3200 MWp production in 2011, or about 15% of the global PV market. CdTe alone accounts for nearly 60% of the thin film production [27].

CdTe cells have theoretical efficiency advantages over competing PV technologies. Efficiency of a PV material is dependent on its inherent band gap. The theoretical maximum efficiency occurs near a band gap of 1.5 eV [65]. CdTe's band gap of 1.44 eV, when compared to other competing PV technologies, is closest to this optimal band gap. Beyond theoretical advantages, CdTe also scores over other PV technologies in actual practice. A comparison of 12 PV technologies that was performed simultaneously in Stuttgart (Germany) and Nicosia (Cyprus) observed that the temperature and irradiance coefficients of CdTe and amorphous silicon cells are the best [58]. The temperature variance of normalized efficiency of PV cells was again the least for CdTe and amorphous silicon cells [92]. These independent experimental results are consistent with the latest specifications from the largest PV cell manufacturers from around the world. CdTe, CIGS, and polysilicon technologies have shown the most improvements in reducing performance degradation rates since the pre-2000 models [53]. In a study conducted in Cyprus, data was collected and analyzed to measure the seasonal performance variance of PV cells over a period of time (2006–2007) under actual field conditions [58]. One of the key findings of this study was that technologies with the lowest temperature coefficients showed the highest annual energy yields. CdTe cells exhibited the second lowest percentage deviation from the normalized seasonal average AC-energy yield and outdoor measured temperature coefficient (PMPP%/K) after amorphous silicon technologies [58]. In terms of performance degradation over time as seen by commercial PV manufacturers, CdTe modules compare well with competing crystalline silicon technologies. The performance warranty offered by First Solar, the largest manufacturer of CdTe PV modules is similar to the warranties offered by competing multi-crystalline and mono-crystalline Silicon PV suppliers. 90%

of the nominal rating is assured for the first 10 years, and 80% for 25 years [24,77,91].

Finally, CdTe scores well over other PV technologies in life cycle emission studies. A comparison of Green House Gas (GHG) emissions across various PV technologies shows that CdTe systems (inclusive of BOS, frame, and module) when compared to ribbon-Si, multi-Si and mono-Si systems emit the least amount of NO_x, SO_x, CO_2 per KWh over the life cycle of deployment [32]. CdTe PV systems (including BOS) also exhibited the lowest indirect emissions for the heavy metals—arsenic, cadmium, chromium, lead, mercury, and nickel [32]. Meta analysis using life cycle emissions of CO_2 from 109 previously published studies of thin film PV technologies [54], and 129 crystalline silicon-based PV cells [49] show that life cycle CO_2 emissions are the least for CdTe PV cells. CdTe technology also scores over other competing technologies when the energy return on energy invested (EROI) is used as a metric, outperforming all silicon technologies by 20–100% [73]. Both EROI and life cycle emissions are important considerations for JNNSM given its linkages to climate change mitigation.

3. CdTe PV and material constraints

There have been both source-side and sink-side concerns surrounding large scale deployment of CdTe PV technology. The central sink-side debate has focussed on potential environmental and health risks associated with cadmium flows given its toxicity. For tellurium, however, the focus has been on potential supply-side bottlenecks that might throttle the growth of CdTe PV. Early fears about cadmium toxicity from the manufacture, use, and disposal of CdTe PV panels have been addressed. During the industrial manufacturing of CdTe cells, cadmium can be safely collected and recycled [31]. Further, over the normal operation of a CdTe PV cell, there are no Cd emissions. This is also true in the case of fire accidents when the glass enclosure prevents release of cadmium [31]. First Solar, the principal manufacturer of CdTe modules, has initiated a safe end-of-life recycling program [25]. Thus, we exclusively focus on investigating supply-side material constraints (Te) and our model does not investigate possible sink-side constraints (Cd).

3.1. Review of cadmium and tellurium metallurgy

Both cadmium and tellurium are currently produced on industrial scale as byproducts of two widely produced metals—zinc and copper, respectively. Simple stoichiometry of a CdTe molecule reveals a molecular mass ratio of 47:53 between cadmium and tellurium. This can be approximated to a 1:1 mass ratio for cadmium and tellurium. Based on this approximation, the amount of cadmium required to meet JNNSM will be considered equal to the tellurium requirements as simulated by the MC model.

3.1.1. Cadmium production in India

The production of cadmium is linked to the extraction of zinc because the raw material input (cadmium sponge) for cadmium purification is a byproduct of zinc extraction [30]. In India, zinc-to-cadmium ratios in the zinc ore, sphalerite (ZnS) range from 0.03% to 9% [37]. Worldwide, the ratio of zinc to cadmium in sphalerite ranges from 200:1 to 400:1 [79]. Cadmium production in India is carried out by two firms which are also responsible for all of India's zinc production [37]. The latest available minerals report from the Indian Bureau of Mines and annual report from the only private entity that produces cadmium in India shows that public sector entities dominate cadmium production in India with private sector contributing only 70 tonnes [9,40]. Publicly available data sources indicate that other large private sector companies, including minerals major Vedanta, do not produce cadmium in India [84].

3.1.2. Tellurium production in India

Tellurium is manufactured commercially as a byproduct of copper, lead, gold, and bismuth production. Around 90% of the world's tellurium is produced as a byproduct of copper refining [30] . Tellurium is recovered from the slime which accumulates during the electrolytic refining of copper [30]. In India, three firms are responsible for the production of copper. Among these three firms, only the government-owned entity which operates over the entire life cycle of copper manufacturing (extraction of ore to finished copper products) produces tellurium as a byproduct of copper production [38]. Anode slime (which is the chief source of tellurium) recovered during the copper production process by one of the private entities is not processed any further in India and is exported to European and other refineries [76]. The other private player does not extract and produce tellurium as a part of its copper manufacturing process [47]. Additionally, the privately owned copper manufacturers in India depend on imported ore [38].

3.2. Global tellurium constraints for CdTe PV

Earlier studies have analyzed probable scarcity scenarios of tellurium for manufacturing CdTe PV cells and the implications they hold for future production costs. Ref. [87] evaluated future extraction costs for 23 semiconductor materials and found CdTe to be the fifth most expensive, and its annual electricity production was the second lowest [87]. There is a significant ambiguity involved in estimates of tellurium reserves, and thus the impact on future manufacturing costs of CdTe PV [11]. Scenario analysis indicates that available tellurium reserves can support CdTe-based solar power production of 1438 GWp in 2020, 19149 GWp in 2050, and 20211 GWp in 2075 [28]. The scenarios were modeled for ‘conservative’ and ‘most likely’ estimates for parameters such as increased primary ore (copper ore) extraction, improved tellurium extraction from copper, increasing efficiency of CdTe cells, reduced refining losses and reduced layer thickness in CdTe cells. This study used actual tellurium extraction data from known copper resources. A study on CdTe PV cells at 16.5% efficiency, with possible tellurium reserves of 47 kilotonnes estimated the power production potential of CdTe PV to be less than a tenth of a terawatt [21]. An earlier study had estimated that for CdTe cells (at 10% efficiency, 1.5 μm layer thickness and an annual mean insolation of 2000 kWh/m^2 of solar cell area) to supply 100 000 TWh/year, the requirement-to-reserve ratio for tellurium was found to be 110 [3]. Consistent with an expanding CdTe PV market, and the uncertainty involved in tellurium constraint estimates, the price for tellurium has seen a sharp 5-fold increase in the last 5 years [63]. A recent study shows that technological progress in various areas tellurium refining and module manufacturing must be modeled in a dynamic rather than a static framework. A dynamic model helps uncover how different pathways for technological progress in refining of tellurium and manufacturing CdTe panels will impact both the market size of these panels and material constraints [48]. However, all assessments of the possible constraints on tellurium availability have been done at the global level. Even in the absence of global constraints, there might be binding national-level material constraints, should a country decide to develop CdTe manufacturing capabilities based on indigenously available feedstock of tellurium. It is important to note here that indigenous material constraints are not independent of larger global constraints as the market and technology pathways in a specific national market evolve in tandem with global trends.

4. A Monte Carlo model of tellurium throughput for JNNSM

As discussed in Section 3.1 the ratio of cadmium and tellurium in a CdTe PV cell is approximately 1:1. We also showed how tellurium rather than cadmium is the binding material constraint for future global expansion of CdTe PV. Thus, in the MC model that we present below, we will formally simulate only the tellurium requirement and set cadmium required equal to the simulated values of tellurium.

Future requirements of tellurium to support the targets envisaged by JNNSM are contingent on many critical technical, policy, and market scenarios. Given that JNNSM targets are two orders of magnitude greater than the current size of PV market in India, history is a very poor predictor of how the PV market might evolve under JNNSM. Modeling the future of the Indian PV market entails combining 'critical uncertainties' into plausible scenarios [15,16,63,86]. MC simulations are particularly well-suited to exploring such critical uncertainties [10,33]. The MC method was first invented by Von Neumann and Ulam who were key members of the Manhattan Project at Los Alamos [56,61,19]. MC simulation experiments have since found applications in a variety of fields [55,26]. The MC method has also been used in energy forecasting and energy policy studies in a variety of settings. Examples include probabilistic models of emissions [85]; and utility expansion scenarios [75].

We develop a MC simulation to probabilistically model the future material efficiency of tellurium in the production of CdTe PV modules, as well as possible market and policy parameters that will impact the technology choices made by JNNSM.

4.1. Model description

JNNSM is a 12-year program started in 2010. The purpose of our simulation is to use JNNSM targets as benchmarks to investigate possible material constraints on indigenous production of CdTe panels rather than accurately track the actual program that is already underway. Let X be the total tellurium throughput required to support all three phases of JNNSM, and $x(t)$ be the annual tellurium throughput in year t:

$$X = \sum_{t=0}^{t=12} x(t) \tag{1}$$

$$x(t) = \eta(t)P(t) \tag{2}$$

In Eq. (2), $\eta(t)$ is the material efficiency of tellurium use (measured as grams of Te required per watt of module output), and $P(t)$ is the aggregate annual CdTe PV capacity addition in year t (measured in[3] Wp, peak-watts).

4.1.1. Modeling annual CdTe module demand

$P(t)$ in Eq. (2) is modeled as

$$P(t) = \gamma(t)\phi(t)\xi \tag{3}$$

The variables in Eq. (3) are defined as follows:

- $\gamma(t)$, *Total annual PV target under JNNSM*: As listed in Table 1, JNNSM is divided into three phases where the targets for total PV installations are ramped up at the end of each phase. In our MC simulation, we let $\gamma(t)$ track the JNNSM targets as follows:

$$\gamma(t) = \begin{cases} 375\ \text{MW} & \forall\ 0 \le t \le 3 \\ 1750\ \text{MW} & \forall\ 4 \le t \le 7 \\ 4000\ \text{MW} & \forall\ 8 \le t \le 12 \end{cases} \tag{4}$$

  For each of the three implementation phases of JNNSM, we assume that annual PV targets remain constant during a particular phase. When the program specifies a range of targets, we simply use the average of the best-case and worst-case scenarios envisaged by JNNSM. Phase-1 has a total PV target of 1000–2000 MW between 2014 and 2017; Phase-2 has a total PV target of 4000–10 000 MW between 2018 and 2022; and the final phase has a total PV target of 20 000 MW to be implemented between 2018 and 2022.
- ξ, *Percentage annual PV target met*: Despite modeling $\gamma(t)$ as an average annual target that is the mid-point of best- and worst-case scenarios under JNNSM, there is a need to take into account the fact that this target is unlikely to be fully realized for policy, market, and engineering reasons. Thus a sensitivity analysis on the model with ξ taking on the following four values: 33%, 50%, 67%, and 90% is performed. The extant literature on tellurium requirements for CdTe PV has extensively utilized comparable scenario based analysis. For example, [93] used similar scenario analysis for the CdTe share of future electricity markets based on layer thickness, cell efficiency, and tellurium supply from the global copper mining industry [93]. Other related examples employing comparable scenario analysis to model tellurium requirements include a three-state scenario (conservative, most-likely, optimistic) for modeling the relationship between layer thickness, cell efficiency, future tellurium requirements [29]; a two-sate scenario for tellurium recovery during copper refining [89]; and a three-state scenario in a dynamic model of market and technological progress [48].
- $\phi(t)$, *Percentage of annual PV target fulfilled by CdTe panels*: First Solar has shipped 200 MW in 2011 (Quarter-1) to India, and has also contracted another 250 MW for 2012 [23]. Assuming First Solar ships another 200 MW in 2013, the total power output of First Solar CdTe cells is 650 MW which is around 32% of the JNNSM Phase-1 grid interactive PV target. Using this information, we model $\phi(t)$ as normally distributed stochastic variable with a mean of 30% and a standard deviation of 5%.

As we discuss in Section 5, the assumptions made above for $\phi(t)$ and ξ are very conservative in light of how the Solar Mission has evolved in the first two batches of Phase-1. Thin film technology accounts for approximately 50% of the total contracted projects amounting to 480 MW [41]. However, the central purpose of our modeling efforts is to understand fundamental material constraints for indigenous production of CdTe PV and conservative assumptions help identify truly binding constraints.

4.1.2. Modeling tellurium efficiency (η)

After having defined the Monte Carlo specifications for $P(t)$, we now specify the probabilistic assumptions for material efficiency, $\eta(t)$ in Eq. (2). There are two sources of technical progress that result in higher material efficiency. First, improvements in manufacturing processes lead to a reduction in the absorber layer thickness of tellurium present in CdTe modules. Second, in addition to reduced film thickness technological progress also results in greater module efficiency [93]. The efficiency variable, η captures both these sources of technological progress driving the decrease of tellurium required per watt of module output:

$$\eta(t) = \rho S(t)\psi(t) \tag{5}$$

In Eq. (5), ρ is the density of tellurium (measured in g/cm^3); $S(t)$ is the surface area required to produce a watt of electrical output (a measure of energy conversion efficiency of the module, measured in cm^2/W); and $\psi(t)$ is the thickness of the tellurium layer. The last few years have seen significant improvements in both conversion and material efficiencies [22,42]. CdTe absorber layer reduced from 3.4 μm in 2004 to 2.1 μm in 2009 [42]. During approximately the

[3] Unless otherwise stated explicitly, all module power measurements used in this paper refer to peak power output. For the sake of notational simplicity, we will use unit such as g/W rather than g/Wp.

same period, the material efficiency (grams of Te required per watt of module output) decreased from 0.1 to 0.091 g/Wp [42,93]. Consequently, the annual year-on-year percentage decrease in tellurium required per watt is modeled as $\lambda(t)$—a normally distributed stochastic variable with a mean of 3% and a standard deviation of 2%.

Recognizing the physical limits of this technological progress, we place a lower limit on the tellurium required per watt on the basis of the minimum required CdTe absorber layer thickness (ψ). The lower limit for CdTe layer thickness is set as 1 μm. Below this value, there is a drop in cell efficiency relative to current industry levels of CdTe cell efficiencies [44,68,60]. The literature reports a wide range of values for the amount of tellurium required per watt of solar power output (up to a factor-of-three variation). Widely cited sources include 100 tonnes of tellurium in 2008 to produce cadmium tellurium material for 358 MW of CdTe cells (0.27 g/W) [15], an assumed value of 0.1 g/W [6], and 0.091 g/W in 2010 [93]. As our purpose here is to identify material constraints for indigenous production of CdTe modules, we will start with the best material efficiency reported in the literature. Thus, we will use 0.091 g/W as tellurium requirement in the base year of our simulation ($\eta(0)$). With these assumptions, the simulation time path for tellurium material efficiency can be written as follows:

$$\eta \ni \begin{cases} \eta(t) = \eta(0)\prod_{t=0}^{t}\lambda(t) \\ \eta(0) = 0.091 \text{ g/W} \\ \psi(t) \geq 1 \mu\text{m } \forall t \end{cases} \tag{6}$$

In order to use the lower bound on absorber thickness ($\psi(t) \geq 1\mu\text{m} \ \forall t$), we will need to consider the relationship between material efficiency defined above ($\eta(t)$) and the module energy efficiency, η_c:

$$\eta_c(t) = \frac{E_O(t), \text{W/cm}^2}{I, \text{ standard solar insolation, W/cm}^2} \tag{7}$$

We use Eqs. (7) and (5) to obtain the lower bound on absorber thickness. Eq. (5) can be rewritten as follows:

$$\psi(t) = \frac{\eta(t)}{\rho S(t)} \tag{8}$$

Note that module area required to produce 1-W output, $S(t)$ is simply a rescaling of the module efficiency, $\eta_c(t)$—by a factor equal to the reciprocal of standard solar insolation:

$$S(t) = \frac{\eta_c}{I} \tag{9}$$

Using recent historical CdTe module efficiency data, we construct a simulation time path for η_c that is similar in structure to the material efficiency model specified in Eq. (6):

$$\eta_c \ni \begin{cases} \eta_c(t) = \eta_c(0)\prod_{t=0}^{t}\lambda_c(t) \\ \eta_c(0) = 14.4\% \\ \eta_c(t) \leq \overline{\eta_c} \ \forall t \\ \overline{\eta_c} = 20\% \end{cases} \tag{10}$$

In Eq. (10), $\lambda_c(t)$ is a year-on-year change in module efficiency modeled as a normally distributed random variable with mean of 8% and standard deviation of 2%. This is based on First Solar's module efficiency improvement over a 5-year period from 9.5% in 2006 to 14.4% in 2011, for a year-on-year efficiency improvement of 8.3% [22]. We specify an upper bound, $\overline{\eta_c}$ in the same way as we specified a lower bound on film thickness. The upper bound for $\overline{\eta_c}$ is set as 20% as the current world record for CdTe cells is 17% [64]. This is consistent with our modeling objective—understanding indigenous material constraints under optimistic assumptions about technological progress.

4.1.3. Modeling copper requirements

Considering the fact that tellurium is extracted as a byproduct of copper, we need to model the amount of copper that will have to be extracted and produced domestically in India to indigenously fulfil tellurium requirements of CdTe panels.

$$s(t) = x(t)/\tau(t) \tag{11}$$

In Eq. (11), $s(t)$ is the amount of copper that will have to be extracted to meet the yearly tellurium requirement $x(t)$. The variable $\tau(t)$ is simply the extraction factor that represents the amount of tellurium that is extracted as a by-product of commercial copper metallurgy. Based on U.S. Geological Survey data for copper and tellurium extraction, the ratio of tellurium extracted to copper extracted ($\tau(t)$) from 1975 to 2003 varies between a lower limit of 5×10^{-6} and an upper limit of 2×10^{-5} [83,82]. Thus, we will model the extraction factor, $\tau(t)$ as a uniformly distributed stochastic variable to be within the range of 5×10^{-6}–2×10^{-5}. Consistent with historical trends, there is no secular trend that we assume for $\tau(t)$ in our 13-year simulation period.

4.1.4. Modeling throughput of primary copper ore

In the final part of our MC model, the copper ore throughput needed to support the demand for copper that will satisfy the requirements of an indigenous tellurium feedstock ($s(t)$ in Eq. (11) is computed. The copper industry in India uses four different grades of ore (of varying copper concentrations). In modeling the ore requirements for supporting an indigenous CdTe PV feedstock, we assume that India's copper supply will continue to be derived from these four major ore grades in the current proportions with some stochastic disturbances as detailed below [38]. Let $M(t)$ be the annual throughput of ore corresponding to the copper requirements, $s(t)$ in Eq. (11). $M(t)$ is modeled as follows:

$$M(t) = s(t)\sum_i \frac{\omega_{it}}{\kappa_{it}} \tag{12}$$

In Eq. (12), ω_{it} is a uniformly distributed stochastic variable representing the proportion of the ore of type i ($i = 1,2,3,4$) in the total copper ore throughput for year t. The ore concentration of ore type i is modeled as κ_{it}. The values for variables ω_{it} and κ_{it} are derived using the present state of copper metallurgy in India as detailed below [38]:

- *Ore with greater than 1.85% copper* ($i = 1$): 2% of the total copper ore in India has this level of concentration [38]. Thus, we model ω_{1t} as a uniformly distributed stochastic variable that takes on a value of 1–2% of the total throughput of copper ore. κ_{1t} is modeled as a uniformly distributed random variable representing ore concentration between 1.85% and 2%.
- *Ore with 1–1.85% copper concentration* ($i = 2$): This grade of copper represents 44% of the total copper ores found in India [38]. Thus, ω_{2t} is modeled as a uniformly distributed random variable that takes on a value of 42–46% of the total throughput of copper ore. κ_{2t} is modeled as a uniformly distributed random variable representing ore concentration between 1% and 1.85%.
- *Ore with 0.5–1% copper concentration ($i = 3$)*: This grade of copper once again represents 44% of the total copper ores found in India [38]. We will therefore model ω_{3t} as a uniformly distributed random variable that takes on a value of 42–46% of the total throughput of copper ore. We define κ_{3t} as a uniformly distributed random variable representing ore concentration between 0.5% and 1%.
- *Ore with copper concentration less than 0.5%* ($i = 4$): 10% of all copper ores in India belongs to this category. The proportion of this ore in the final mix (ω_{4t}) will be modeled as a residual—the remainder proportion that is needed to satisfy the copper

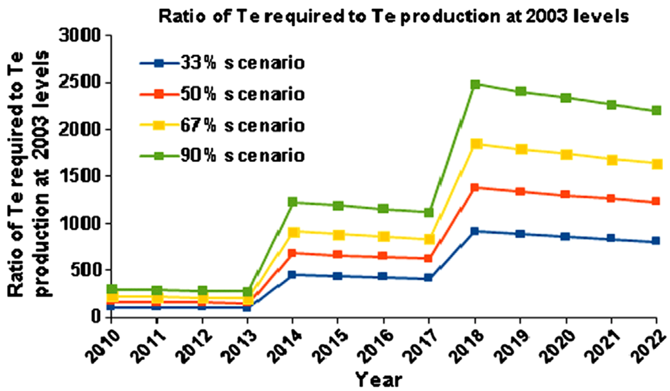


Fig. 4. Tellurium requirements for meeting JNNSM targets. The figure graphs the ratio of Te required for meeting JNNSM targets (as predicted by the Monte Carlo model) in any given year, and indigenous Te production in 2003 (the latest year for which data is available).The four scenarios correspond to assumptions about annual PV targets achieved under JNNSM (ξ in the model).

demand for CdTe PV.

$$\omega_{4t} = 1 - \sum_{i=1}^{i=3} \omega_{it} \ni M(t) = s(t) \sum_{i=1}^{i=4} \frac{\omega_{it}}{\kappa_{it}}$$

The ore density, κ_{4t} is defined as a uniformly distributed random variable between 0% and 0.5% copper concentration.

The appendix describes the outline of the software implementation of the model described in this section.

4.2. Model results

4.2.1. Tellurium

As detailed in Appendix A, we ran the model ten times with 10 000 trials in each run. For each run, the annual tellurium requirement is calculated as a simple average of tellurium requirement calculated in each of the 10 000 trials.[4] Fig. 4 presents the results of the simulation.

Fig. 4 scales the annual tellurium requirement for each year using the tellurium produced indigenously in India (31 kg; 2003 data, the latest available [34]). For example in 2014, assuming 50% of the targets set by JNNSM are met, tellurium required to produce CdTe cells will be almost 700 times the 2003 tellurium production in India. Similarly the blue, yellow and green points in 2014 indicate the ratio of tellurium required to tellurium produced in India in 2003 if 33%, 67% and 90% respectively of JNNSM targets are met. While scaling tellurium requirements with a fixed base year production will overstate the material gap, a ratio of 700 is unlikely to be bridged even under most optimistic assumptions if rising tellurium production were accounted for in a dynamic model setting [48]. As seen from the figure, by the third phase of JNNSM, tellurium shortfall is over 500 times the 2003 production even under the most pessimistic assumptions about how PV targets are achieved under JNNSM, and this shortfall is over 2000 times if JNNSM achieves 90% of PV targets envisaged under the program.

4.2.2. Copper ore

Our model not only simulated the amount of tellurium required but also the primary copper ore throughput needed to supply the annual tellurium feedstock required by JNNSM. Fig. 5 presents the annual copper ore throughput required, scaled by 2010 ore throughput. Tellurium is primarily produced as a byproduct of copper, and Fig. 5 indicates that indigenous production of CdTe modules to support the ambitious JNNSM targets faces a fundamental material constraint given the current levels of copper metallurgy in India. With only one primary-copper manufacturer in India producing tellurium as a byproduct, India faces operational constraints if it intends to scale up tellurium extraction from copper extraction even if copper production were to greatly expand. For example in 2017, assuming 50% of the targets set by JNNSM are met, copper ore required (to produce tellurium) will be 50 times the total copper ore extracted in India in 2010.

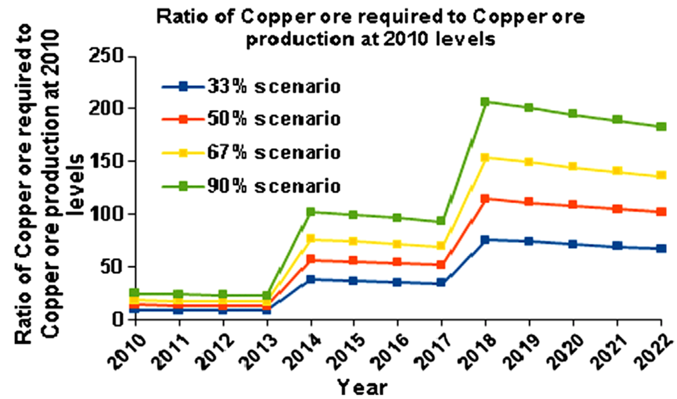


Fig. 5. Copper ore throughput required to meet JNNSM targets. The figure graphs the copper ore throughput required to meet Te demand as calculated by the Monte Carlo simulation (Fig. 4). The required throughput is expressed as a ratio of annual demand from JNNSM to the throughput in 2010.

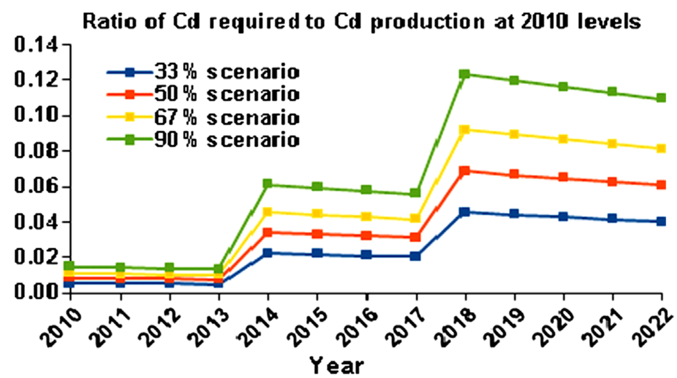


Fig. 6. Cadmium requirement for meeting JNNSM targets. The figure graphs the ratio of Cd required for meeting JNNSM targets (as predicted by the Monte Carlo model for Te) in any given year, and indigenous Cd production in 2010, using the same scenarios described in Fig. 4.

4.2.3. Cadmium

As noted earlier, stoichiometry of the CdTe molecule allows for a 1:1 approximation for Cd:Te mass ratio (the exact molecular mass ratio is 47:53). Based on this approximation, the annual cadmium requirements for supporting JNNSM targets are presented in Fig. 6. Thus, the annual cadmium requirements are the same as annual tellurium requirements. However, cadmium production in India in 2010 stands at 553 tonnes [37] which is much higher than the cadmium requirements to meet JNNSM targets. Fig. 6 shows the annual cadmium requirements scaled by 2010 production of cadmium. As seen from the figure, cadmium is not the material bottleneck for indigenous production of CdTe cells. For example in 2014, assuming 33% of the targets set by JNNSM are

[4] For an exposition on number of trials needed for convergence, see [7,17]. Our iteration count is more than sufficient for clear convergence of first order statistics that is our interest here.

met (the blue line), the cadmium required (to manufacture CdTe PV cells) will be only 0.02 times the cadmium produced in India in 2010. Similarly the red, yellow and green points in 2014 indicate the ratio of cadmium required (to manufacture CdTe PV cells) to the cadmium produced in India in 2010 if 50%, 67% and 90% of JNNSM targets are met from 2010 to 2022.

5. Discussion

As seen from the model results, the binding material constraint for indigenous production of CdTe modules is the availability of solar grade tellurium. There are two parts for this constraint. First, the current size of the Indian copper refining industry cannot support the throughput of tellurium required for indigenous manufacture of CdTe modules. Second, even if the Indian copper industry were to expand, India will have to upgrade its tellurium recovery rates from the copper refining process. Given the current state of copper metallurgy and size of the primary copper production industry in India, JNNSM cannot simultaneously fulfill its twin goals of deploying the most cost-effective PV configurations *and* bootstrapping an indigenous PV manufacturing capacity. India has already imported around 200 MW of CdTe cells in 2011 (Quarter-1) and has contracted another 250 MW of CdTe cells for 2012 from First Solar [23]. These imports account for nearly 50% of contracted projects from the first two batches of the Solar Mission Programme [41]. If India continues to rely on PV imports, it might potentially impact the policy goal of developing a domestic industry to produce solar cells. Alternatively, India can develop manufacturing capabilities for older silicon-based technologies that face no fundamental material constraints but India will miss an opportunity to get an indigenous foothold in one of the most promising PV technologies.

Our results are based on conservative assumptions about JNNSM's scope. First, we have assumed that CdTe panels will be used only for grid-interactive PV and not for stand-alone projects. The solar mission envisages 3200 MW of off-grid PV in the program—over 10% of the median grid interactive targets that are modeled here. Second, it is assumed that the solar mission program is likely to achieve the median rather than higher end of the targets in the first two phases of the program. If the trends observed in Phase-1 hold through the duration of the programme (approximately 500 MW already contracted), the results based on our conservative assumptions will understate the severity of tellurium constraint under a large-scale indigenization programme for thin films [41]. Finally, JNNSM is envisaged as a catalyst that will spur further growth beyond the program. Even if the bulk of CdTe panels used during the program are imported, India will have to confront this binding material constraint at some point in the future.

Our analysis here suggests that as part of its thrust on developing an indigenous PV industry, JNNSM must also focus on increasing tellurium recovery from existing copper producers in India even if it is not going to solve the fundamental material constraint. Even at current levels India's copper ore production from 2000 to 2010 is in the range of 2 642 706 tonnes to 3 498 270 tonnes [39]. Assuming a mean value of 3 070 488 tonnes of copper ore production, and using the extraction factors and ore concentration distribution from the MC model, 250 kg of tellurium can be extracted—roughly eight times approximately 30 kg that India currently produces.

6. Conclusion

One of the attractive features of India's National Solar Mission is that it is agnostic about the actual PV technology that would be deployed under the program. While CdTe technology offers several technical and economic advantages over silicon technologies, India will do well to indigenously develop a diverse manufacturing base for an array of PV technologies so that it does not encounter any binding material constraint. The first 2 years of JNNSM has witnessed a major shakeup of the PV market in India. As of September 2012, close to 80% of the domestic manufacturing units have been shutdown following a glut of cheap imports [90]. A current loophole in the JNNSM policy has exempted thin film PV technology from indigenization requirements. Consequently, US manufacturers supported by the US EXIM bank enjoy virtual monopoly [90].

The impetus for an indigenous manufacturing base for PV technology arises from both economic and national security considerations. For example, the United States recently imposed steep tariffs on PV modules from China to protect its domestic solar industry that it sees as a potential engine of economic revival besides being a strategic industry [12]. With the added imperative of reducing dependence on fossils to combat climate change, national-level material constraints for expansion of renewable energy assume new salience. Material constraint analysis (including at the national level) must be incorporated into all future renewable energy scenarios. Beyond JNNSM, the analysis presented in this paper demonstrates the need for focussing on national-level material constraints in addition to global constraints. The MC model presented in this paper can serve as a template for future material constraint analysis at the national level even when indigenous production of thin film PV in India might not take off as part of its National Solar Mission. The current policy in force allows import of thin film cells for the foreseeable future. Indeed the large share of thin film technology in the first two batches of the Solar Mission suggests that indigenous production of thin film PV might not materialize.

Acknowledgments

We would like to thank A.D. Chitralekha for stylistic comments that greatly contributed to an improvement in exposition. Siddharth Joshi, Anish Sugatan, H. Venuprasad, and two anonymous reviewers provided comments on an earlier draft. We are responsible for all remaining errors. The research reported here was carried out when Ravikumar was affiliated with the Indian Institute of Management Bangalore, India.

Appendix A. The simulation algorithm

1. Obtain the value of $\xi(t)$ from the following: 33%, 50%, 67%, 90%.
2. For every year, t:

   (a) $$\gamma(t) = \{375\,000\,000 \text{ W for } 2010 \le t \le 2014$$
   $$1\,750\,000\,000 \text{ W for } 2014 \le t \le 2017$$
   $$4\,000\,000\,000 \text{ W for } 2018 \le t \le 2022\}$$

   (b) Draw $\phi(t)$ from the normal distribution ($\mu = 30\%$ and $\sigma = 5\%$)
   (c) Calculate $P(t)$ using Eq. (3)
   (d) Let the module efficiency ($\eta_c(t)$) in the base year 2010 be 14.4%. For every subsequent year increase the module efficiency by a random variable ($\lambda_c(t)$) drawn from the normal distribution ($\mu = 8\%$ and $\sigma = 2\%$). The module efficiency should be capped at a ceiling value of 20%.

(e) Divide the module efficiency $\eta_c(t)$ (generated in step 2d) by the standard insolation of 1000 W/m^2 as indicated in Eq. (9). This gives the value of $S(t)$.
(f) The tellurium required per watt $(\eta)(t)$ of solar power is 0.091 g in the base year 2010. Calculate $\psi(t)$ as indicated in Eq. (8) based on the values of $S(t)$ (from step 2e), $\eta(t)$ and the standard density of CdTe (ρ). Only if the value of $\psi(t)$ is greater than 1μm then for the subsequent year reduce the value of $\eta(t)$ by a percentage determined by the random variable $(\lambda)(t)$ drawn from the normal distribution ($\mu = 3\%$ and $\sigma = 2\%$)
(g) Calculate $x(t)$ based on $P(t)$ (step 2c) and $\eta(t)$ (step 2f) using Eq. (2)
(h) Repeat steps 2b, 2c, 2d, 2e, 2f, 2g 10 000 times and obtain the average value of $x(t)$ using Eq. (2)

3. Calculate X using Eq. (1)
4. Repeat step 2 and step 3 ten times to obtain ten different values of X. Run this step for each of the years between 2010 and 2022.
5. Perform a sensitivity analysis on $\xi(t)$ by repeating step 4 for the remaining values of $\xi(t)$ (from step 1) to get four result sets for the four values of $\xi(t)$. Each result set will have 10 values of tellurium required per year for each of the 13 years over which the simulation is run.
6. Generate 10 000 values each for ω within the following ranges:
   (a) $\omega_{i=1}$ is a uniformly distributed stochastic variable that ranges from 1 to 2%
   (b) $\omega_{i=2}$ is a uniformly distributed stochastic variable that ranges from 42 to 46%
   (c) $\omega_{i=3}$ is a uniformly distributed stochastic variable that ranges from 42 to 46%
   (d) $\omega_{i=4}$ is the percentage of copper ore that is complements the above three grades to the complete yearly copper ore extraction
7. Generate 10 000 values each for κ within the following ranges:
   (a) $\kappa_{i=1}$ is a uniformly distributed stochastic variable that ranges from 1.85 to 2%
   (b) $\kappa_{i=2}$ is a uniformly distributed stochastic variable that ranges from 1 to 1.85%
   (c) $\kappa_{i=3}$ is a uniformly distributed stochastic variable that ranges from 0.5 to 1%
   (d) $\kappa_{i=4}$ is a uniformly distributed stochastic variable that ranges from 0 to 0.5%
8. Along with the 4 sets of tellurium values generated in step-5 generate 10 000 values of the extraction factor $\tau(t)$ and calculate ten thousand values of copper required by using Eq. (11). Based on the copper values generated and the values of ω and κ generated, respectively, in steps 6 and 7 we calculate the copper ore requirements through Eq. (12)
9. Calculate the mean of the 10 000 values of copper ore obtained in step 8 to get 4 sets of copper ore requirements. Each set will have 10 values of copper ore for each of the 13 years over which the simulation is run. The values of copper ore thus got will be compared to copper ore extraction in India to give insights into the supply side constraints of copper ore in India which is the chief raw material for tellurium extraction.

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